JPL 1990-3: A 5-nrad Extragalactic Source Catalog Based on Combined Radio Interferometric Observations

O. J. Sovers
Tracking Systems and Applications Section

A combined analysis merges 17,000 DSN Very Long Baseline Interferometric (VLBI) observations with 303,000 observations from the Crustal Dynamics Project (CDP) and the International Radio Interferometric Surveying (IRIS) project. Observations from the Radio Reference Frame Development (RRFD) and Time and Earth Motion Precision Observations (TEMPO) programs through late 1990 form the DSN VLBI data set. The combined analysis yields angular coordinates of extragalactic radio sources with a precision of a few nanoradians, as compared with 5- to 10-nrad precision for coordinates derived in the past solely from DSN data. The improvement in the combined analysis is due to the new Mark III DSN data, as well as to increased statistical strength from the large volume of observations from non-DSN experiments. Such a unified analysis is made possible by recent improvements in parameter estimation software efficiency. The terrestrial reference frame is based on joint VLBI experiments employing both DSN and CDP antennas, and on specifying the coordinates of VLBI antennas in a proper geocentric coordinate system by means of Global Positioning System (GPS) collocation of VLBI, LLR, and SLR (Lunar and Satellite Laser Ranging) sites. Approximately 200 sources, fairly uniformly distributed over the sky at declinations ranging from −45 to +90 deg, form the 1990-3 catalog, and show formal uncertainties smaller than 5 nrad. At this level of precision, it is critical to estimate corrections to the International Astronomical Union (IAU) models of precession and nutation, and the 1990-3 source positions should only be used in conjunction with these corrections. Furthermore, at this level, a number of ignored effects, such as tropospheric turbulence and source structure, may cause errors equal to or greater than the formal uncertainties. Attempts to assess the influence of unmodeled systematic errors by comparing source positions with catalogs derived from independent analyses of partially independent data place a lower limit of 2 to 3 nrad on currently achievable accuracies. This leads to a realistic estimate of the true level of accuracy of approximately 5 nrad for this combined radio source catalog.

I. Introduction

This work emerged from a comparison of the models and analysis techniques employed by Goddard Space Flight Center (GSFC) and JPL groups [1]. Subsequently, it became of interest to determine whether adding non-DSN data to the analyses for radio-reference frame development could compensate for the reduced availability of the DSN antennas for Very Long Baseline Interferometry (VLBI) in the late 1980s. A further goal was to determine how much is to be gained by adding non-DSN data to the databases determining previously published JPL source coordinates [2,3], as well as to the more recent DSN-only data including several thousand Mark III observations [4]. By mid-1990 the total number of VLBI observations available for processing at JPL had exceeded 300,000. Recent improvements in JPL analysis software have made it possible to perform least-squares estimation involving hundreds of thousands of observations and tens of thousands of parameters within a few days of CPU time on VAX-780–class computers. It was therefore decided to generate a radio source catalog from all the VLBI data available in order to assess its suitability for meeting navigation requirements.

Three current projects demand celestial or terrestrial reference frames at or exceeding the accuracy levels of current frames. Proposed Galileo tracking requirements specify a radio reference frame stable to 5 nrad, while preliminary specifications for Ka-band tracking of Cassini tighten this requirement to 3 nrad. The TOPEX-POSEIDON project requires 3-cm three-dimensional baseline accuracy, with 5-cm alignment with the geocenter. This translates to 3 nrad on the California–Australia baseline. Thus, navigation requirements in the near future are more stringent than the accuracy level of 10 nrad for the DSN reference frame published in 1988 [2], and also go beyond the more recent DSN source catalogs [3,4].

The Crustal Dynamics Project (CDP) and International Radio Interferometric Surveying (IRIS) programs always perform multiple baseline experiments, with much more frequent observing sessions than those of the DSN. Consequently, the number of CDP+IRIS observations is more than an order of magnitude larger than the number of DSN observations generated by the Radio Reference Frame Development (RRFD) and Time and Earth Motion Precision Observations (TEMPO) projects at JPL. The CDP and IRIS networks also provide a considerably different geometrical coverage of the Earth than the three DSN complexes, and may thus serve to expose any systematic effects which depend on network geometry.

The combined VLBI database consists of 319,734 observations. In addition to being one of the largest data sets used for estimation of astrometric and geodetic parameters, it also provides a diverse set of baseline lengths and orientations. A long-standing weakness of all current VLBI data is the paucity of observations by stations in the southern hemisphere. This is especially true of the CDP and IRIS measurements throughout the 1980s; the DSN has benefitted from the Tidbinbilla station, which permits sky coverage down to −45-deg declination. On the other hand, all the non-DSN data have been acquired with Mark III recording systems, which have only recently (1988) been introduced into the DSN. The larger DSN antenna diameters and lower system temperatures, however, produce markedly reduced system noise and observable errors in current DSN Mark III data relative to CDP and IRIS data.

Aside from possible systematic errors, the radio source positions reported here form one of the best-determined extragalactic source catalogs presently available, which is a candidate for a fundamental reference frame. Discussions are under way in various International Astronomical Union (IAU) working groups, which are expected to adopt (in 1994) a radio reference frame to replace the present optical-based frame as the fundamental reference frame for astrometry. Such considerations are driven by the realization that uncertainties of the best optical measurements presently exceed the best radio interferometric uncertainties by at least an order of magnitude: <5 nrad (radio) versus ≈100 nrad (optical) [5]. When the next generation of optical astrometric measurements of galactic sources becomes available from the Hipparcos project [6], optical uncertainties are expected to be reduced to 10 nrad. Unlike the extragalactic radio sources, however, most galactic optical objects show considerable proper motion. As a result, the source positions reported here form a more stable reference frame than Hipparcos. During the next few years, additional experiments by the astrometry groups at the Naval Research Laboratory (NRL) and the U.S. Naval Observatory (USNO), as well as other current projects, are expected to improve precision further and to provide more nearly uniform sky coverage by including southern hemisphere observations.

This article presents a description of the analysis of combined VLBI observations. Section II summarizes the interferometric data from the four projects that are employed to generate the combined source catalog. Details such as distribution of observing sites, noise characteristics, and elevation angles serve to characterize the observations. VLBI modeling, analysis, and parametrization are discussed in Section III, while Section IV gives a summary of the results most pertinent to specification of radio source coordinates for spacecraft navigation. Section V attempts an assessment of the influence of unmodeled systematic errors in order to arrive at realistic estimates of the true level of accuracy of the combined radio source catalog.

II. VLBI Data

Only data from experiments employing hydrogen maser frequency standards and dual-frequency (S- and X-band, 2.3 and 8.4 GHz) ionosphere calibration are considered here. This means that no data prior to 1978 are included. Mark III VLBI systems [7] were used in acquiring all the CDP and IRIS data, and Block I systems [8] were used in TEMPO, while Mark II systems[1,2] were employed in RRFD experiments until late 1988 to early 1989, with Mark III used thereafter.

A short summary of the four observing programs that are considered in this article is presented in Table 1. Further details concerning data acquisition, reduction, and analysis are given in [9] for the GSFC CDP data, and in any current IRIS monthly bulletin [10] for the National Geodetic Survey IRIS data. Here, N_{stn} is the number of unique stations, and N_{bsl} is the number of unique baselines. Note that no distinction is made among various antennas at the three DSN complexes (marked with asterisks). The number of observing sessions is N_{ses}; these are normally of 24-hr duration (except for the post-1987 RRFD and the 3-hr TEMPO sessions), and may involve as many as seven stations. The number of unique sources observed in each program is N_{src}. The major thrust of the first three observing programs of Table 1 is geodetic, while the RRFD program is predominantly astrometric, as can be seen from the N_{bsl} and N_{src} columns. An order of magnitude more observations of relatively few sources by CDP, and especially IRIS, may contribute more to determination of short-period nutation amplitudes than to improving the accuracy of source positions. Finally, N_{obs} is the number of pairs of delay (D) and delay-rate (DR) measurements that are included in the analysis. The analysis described here used data available in the fall of 1990; by early spring of 1991, the number of RRFD MkIII observations had tripled, and they are being incorporated into the database for a future source catalog. A total of 230 extragalactic radio sources contributed observations. The number of observations per source ranges from a maximum of 23,656 (for 4C 39.25) to 1 (for five sources for which RRFD observations had only recently begun).

Two broad characterizations of the data involve data-noise and elevation-angle distributions. Table 2 shows the root-mean-square delay data noise (formal uncertainty from correlation processing) for each observing program, as well as the additional noise (constant for each baseline in a given observing session) that was root-sum-squared with the observable noise in order to approximate chi-square per degree of freedom = 1 in the least-squares fit (see Section III). Note that for TEMPO data, additional noise is introduced as an RSSed fraction of the total tropospheric delay contribution for each observation [4], rather than as an RSSed constant for each observing session. The RRFD data are subdivided into Mark II and Mark III categories because there is a large difference in their data quality. While the data quality also generally improves with time from the late 1970s to 1990 for all observing programs, there is no such clear demarcation for CDP, IRIS, or TEMPO.

It can be seen that both the data noise and additive noise are considerably lower for CDP and IRIS data than for RRFD MkII and TEMPO data. The RRFD MkIII data, on the other hand, exhibit the lowest value in both categories. Comparison of data noise and additive noise is not straightforward because of variations in scan lengths and fractions of low-elevation observations among the observing programs. Variation of the additive noise may indicate problems either with the receiving or recording systems, correlation processing, data editing, or the post-correlation software that generates the observables. Noise added to account solely for unmodeled physical effects is not expected to vary with the type of data if similar observing schedules are used. The strength of the DSN data as a whole lies in the larger antennas and variety of sources observed, as well as the generally longer baselines and more complete declination coverage. The DSN observations also benefit from quieter receiving electronics, given equivalent recording systems. These characteristics permit the 17,000 DSN observations to make a nearly equivalent contribution, on the whole, to that of the 300,000 CDP+IRIS observations in the combined fit.

Low-elevation-angle observations were avoided in early non-DSN VLBI experiments because of problems in modeling the large tropospheric delays at low elevations. As a result, there is a scarcity of data at elevation angles below 15–20 deg in the early CDP and IRIS data. The DSN experiments, partly because they were performed over longer baselines, routinely involved observations down to the an-

[1] E. J. Cohen, "VLBI Bandwidth Synthesis Manual," JPL Tracking Systems and Applications Section report (internal document), June 1979.

[2] E. J. Cohen, "VLBI Rack Manual," JPL Tracking Systems and Applications Section report (internal document), May 1980.

tenna limits of 6-deg elevation throughout their entire history. Now that improved troposphere models are available [11,12], and it is commonly accepted that mismodeling of the time-varying tropospheric delay is a limiting error source in interpretation of VLBI results [13], and that low-elevation observations help to model and reduce the static part of this error, CDP and IRIS experiments also routinely acquire substantial numbers of low-elevation observations. Table 3 shows an overall summary of the four observing programs in terms of the fractions of observations involving elevation angles smaller than 10, 20, and 30 deg (f_{10}, f_{20}, and f_{30}, respectively) at any participating station. It may be seen that both f_{10} and f_{20} are larger by approximately a factor of 3 for RRFD and TEMPO than for CDP and IRIS observations. Well over half of the DSN observations are made at elevations below 30 deg.

Two analyses of comparably large VLBI data sets have been recently carried out by Ma and co-workers [14,15]. These two catalogs are based respectively on 237,000 and 461,000 observations, with the second including NAVNET (the geodetic VLBI program of the USNO) and southern hemisphere astrometric data in addition to CDP and IRIS experiments. There is necessarily considerable overlap between those two databases and the one used in the work described here. Comparison of estimated source positions indicates the magnitude of discrepancies due to differences in observables, modeling software, and analysis techniques.

III. Modeling and Data Analysis

With some exceptions, theoretical modeling of the observed delays and rates conforms to the specifications contained in the International Earth Rotation Service (IERS) standards [16]. The data quality demands a model for the Earth's precession and nutation that goes beyond the current IERS and IAU standards [17]. Details are given below, and a more complete description of modeling is given in the document concerning the JPL VLBI software "MODEST" [18]. Briefly, the calculations are performed in solar system barycentric coordinates defined in terms of the mean equator of J2000.0.

The clock and troposphere modeling options were the same as those used in the 1988 source catalog paper [2]. The clock model was piecewise linear, with breaks introduced only in places where they appeared essential from inspection of the post-fit residual patterns. At most stations, this averaged to 5 or 6 clock sections per 24 hr. Improved instrumental stability reduces this by at least a factor of 2 for RRFD Mark III data. Troposphere modeling was piecewise constant, with a new value of the zenith delay estimated at each station for every 3 hr of observations. It remains to be determined how much error in source coordinates is introduced by such parametrization.

UT1 and polar motion (UTPM) values were fixed at those given by the uniformly smoothed time series of Gross and Steppe [19], which is consistent with the 1989 IERS UTPM reference frame [20]. These Earth-rotation parameters are accurate to 1 to 2 nrad during the latter part of the time span covered by the VLBI data. The coordinates of the reference station (Gilmore Creek, Alaska) were taken from the CDP Annual Report for 1989 [9] at the epoch 1988.0. These coordinates are specified in terms of a current best-estimate geocentric system, established in recent years by means of comparison of VLBI, SLR, LLR, and GPS measurements [21]. Positions at epoch 1988.0 are estimated for 30 stations (all but the reference station). Except for Gilmore Creek, time rates of change are also estimated for the coordinates of all stations for which the data cover a sufficient time span (19 stations in all).

Note that the adoption of a terrestrial reference frame poses a consistency problem in analysis of large data sets. Considerable portions of the data used here have also gone into the results of all the references cited in the previous paragraph. Achieving truly independent fixes of the terrestrial coordinate system and the UTPM series would necessitate the adoption of results of techniques totally independent of VLBI. Satellite and lunar ranging techniques, however, are presently not capable of providing all the required parameters at an acceptable accuracy level.

Similar considerations apply, to a somewhat lesser degree, to the method used to circumvent the right ascension reference problem for VLBI data. The origin of celestial coordinates was fixed by tightly constraining the right ascension and declination of OJ 287 and declination of CTD 20 to their values in the IERS 90C01 celestial reference frame [20]. Instead of the usual single right ascension constraint, three coordinates are constrained in order to allow for improved nutation and precession models, and to make the overall orientation of the estimated coordinate system be close to IERS 90C01. It was noted from previous experience that alternative choices of terrestrial and celestial origins have little effect on the relative source coordinates. Nutation modeling is a known weak point of the present IERS standards, which use the 1980 IAU nutation series [17]. The position of the celestial pole is known to depart from the 1980 IAU value by as much as 25 nrad [4,22,23]. The quality of present VLBI data demands that this inadequacy be compensated by some means. Consequently, it was decided to estimate values of the precession constant and selected nutation amplitudes.

Ecliptic longitude (ψ) and obliquity (ε) define the position of the celestial ephemeris pole (CEP) at a given epoch. The estimated components of the nutation model were the amplitudes of the nutations with selected periods in both longitude and obliquity. There is evidence [24] that effects of ocean tides and friction at the core–mantle boundary cause small contributions to nutation that are out of phase with those of the current IAU model, which was derived for an oceanless Earth. Consequently both in-phase and out-of-phase components were considered. Amplitude corrections ΔA_ψ and ΔA_ε of a total of nine nutation periods were estimated: 18.6 yr, 9.3 yr, 365.3 d, 182.6 d, 121.7 d, 27.6 d, 13.7 d, 13.6 d (respectively, terms 1, 2, 10, 9, 11, 32, 31, and 33 of the total of 106 in the 1980 IAU series), and the free core nutation with a period of 433.2 d. These particular frequencies include at least all the terms which have been found to require amplitude corrections in previous work [22,23]. Exploratory fits on various subsets of the present database have shown that the 18-yr, annual, and semiannual terms give a good representation of the daily corrections to the CEP position ($\Delta\psi$ and $\Delta\varepsilon$) determined from the data. The remaining terms are included here in order to uncover other, possibly significant corrections. With 4 components per period, the total number of estimated nutation amplitudes was 36. In order to constrain the celestial ephemeris pole at epoch J2000 to its nominal position, two angular offsets (rotations about the x and y axes) were also estimated. These represent, respectively, displacements of the CEP toward 18- and 0-hr right ascension. The method used here for defining the celestial reference frame and for estimating precession and nutation follows [4].

A linear least-squares algorithm is used to obtain optimal estimates of the model parameters from data. The least-squares estimation is achieved with the square-root information filter (SRIF) algorithms of Bierman [25]. The software is presently implemented on VAX computers and workstations, which were used in the fit described in this article. Several days to a week of CPU time is required to complete the analysis. Disk storage requirements are also quite sizable ($\approx$0.5 Gbytes), mostly due to the large number of source coordinates that enter each fit as global parameters. To minimize CPU and storage requirements, the analysis was done in six sections: two CDP, three IRIS, and one RRFD/TEMPO, with no section containing more than 70,000 observations. The basic fit estimates 57,795 parameters from the 319,734 pairs of delay and delay-rate observables. Of these, only the 460 source coordinates, 39 nutation/precession quantities, and 294 station positions and rates were global parameters. The final combined results are identical to what would be obtained by performing the fit in a single step [25].

The least-squares parameter estimation is weighted by a covariance matrix of the observables that is diagonal. The diagonal elements are inversely proportional to the square of the observable error. Such effects as uncalibrated instrumental errors, troposphere fluctuations [13], and source structure [26–28] introduce additional unmodeled noise. In order to partially account for these inadequacies, session-specific adjustable errors are introduced. As mentioned in Section II, these are root-sum-squared with the observable errors, and adjusted in order to make the normalized chi-square for each session close to 1.0. For delays, this additive noise ranges from a few to tens of picoseconds for Mark III observations, to several hundred picoseconds for some of the early Mark II and Block I sessions. As mentioned before, the variation of additive noise may indicate possible problems in instrumentation, correlation, or postcorrelation processing that need to be investigated further.

IV. Results

The overall goodness of fit is indicated by root-mean-square (RMS) residuals of 123 psec for delays, and 100 fsec/sec for delay rates. These are distributed among the component data sets, as shown in Table 4. Generally, the residuals fall into two classes: Mark II (TEMPO and RRFD) and Mark III (CDP, IRIS, and RRFD). The noticeably better IRIS DR residuals may originate in the smaller proportion of IRIS low-elevation observations. Since this article focuses on the celestial reference frame, three categories of estimated parameters (clock, troposphere, and station location) will not be considered in detail here. The first two categories (clocks and tropospheres) will be subject to future scrutiny in order to better characterize their stochastic behavior. Station coordinates at epoch 1988.0 are generally determined with formal uncertainties of $\approx$2 to 20 mm, and their linear time rates of change with uncertainties of $\approx$1 to 5 mm/yr. The rates agree with the Minster-Jordan AM0-2 [29] and NUVEL [30] models of tectonic motion at the level of a few mm/yr. Naturally there is an intimate relationship between the models of UTPM and tectonic motion, which needs to be explored more critically in future work.

Not counting the two reference sources (OJ 287 and CTD 20), coordinate estimates are made for a total of 230 sources. Positions of 216 of these sources are listed in Table 5, including the number of observations, average observing epoch, and correlation coefficient between right ascension and declination. Note that the source coordinates are given in the traditional units of hours, minutes, and seconds for RA, and degrees, minutes, and seconds for declination (δ). Approximate conversion factors to nanoradians are $72\cos(\delta)$ nrad/msec for RA and 4.8 nrad/mas for δ. Fourteen sources with 1σ declination uncertainties that exceed $\approx$20 nrad are not included in Table 5. On the other hand, the Table includes 23 sources with fewer than 10 observations, whose coordinates should be considered preliminary. Most of these are sources for which DSN observations have been initiated only recently. Nevertheless, approximately half of these sources have σ's smaller than 5 nrad. To give the reader some idea of the quality of this catalog, it contains 40 sources that were observed more than 1000 times, 54 sources with formal declination uncertainties (σ_δ) smaller than 1 nrad, and a majority (178) of the sources have $\sigma_\delta < 5$ nrad. The catalog is named JPL 1990-3, in conformance with the local naming convention which categorizes catalogs by date of analysis.

Figures 1(a) and (b) show histograms of the formal uncertainties of JPL 1990-3 divided into 0.25-nrad bins. For comparison, similar histograms are shown in Figs. 2(a) and (b) for the current TEMPO catalog, JPL 1991-1 [4], which is based on DSN data through early 1991. It is seen that the errors of 1991-1 bear some resemblance to single-peaked distributions, while the heterogeneous nature of the observations entering 1990-3 spreads out the error distributions considerably and introduces multiple peaks.

Table 6 shows the precession and nutation parameters (in units of nanoradians) derived from the fit which yield JPL 1990-3. Note the highly significant precession correction. The x and y celestial ephemeris pole offsets are listed in the ΔA_ψ and ΔA_ε columns, and show that the CEP at J2000 is significantly shifted, approximately toward 5.5 hours RA. There are sizable significant corrections to the 1980 IAU nutation amplitudes at 18-yr, 9-yr, annual, and semiannual periods, including a number of out-of-phase components. A number of the shorter-period nutation amplitudes are not significant, judging by the given formal uncertainties, but are included for completeness. A long-standing problem in estimating precession and nutation quantities is the short timebase of VLBI observations relative to the 18.6-yr nutation period. This leads to high correlations between precession and nutation, and the problem is not expected to be fully removed until the data cover a full 18.6-yr cycle in the late 1990s. The formal uncertainties in Table 6 should be interpreted with these high correlations in mind (the largest correlation coefficient between precession and nutation is 0.93). Nevertheless, there is substantial agreement of these values with comparable theoretical [31,32] and experimental [22,33] estimates. Note that the quoted experimental results use data that partly overlap the data used here. It is stressed that any application using the source coordinates of Table 5 must also model the celestial pole position with the parameters of Table 6.

V. Consistency Tests and Accuracy Estimates

The database involved in generating the radio source coordinates presented here is too large to permit many internal consistency tests to be carried out within a reasonable time span, with the computing facilities currently available. Therefore, assessment of the validity of the formal 1σ statistical parameter uncertainties was performed by comparison of the estimated coordinates with those of a variety of other catalogs, based on data that overlap the present database to varying degrees.

The first category of such catalogs includes those based only on RRFD and TEMPO data. The DSN catalogs JPL 1987-1 [2] and JPL 1991-1 [4] are selected for comparison with JPL 1990-3. Catalog JPL 1987-1 contains positions of 128 sources, and is the last DSN catalog described in an external refereed publication. Note that data entering 1987-1 terminate in late 1985, well before the inception of DSN Mark III systems. Catalog JPL 1991-1 is the current TEMPO catalog, based on RRFD and TEMPO data through early 1991, and thus includes more sources (241) and more than twice the number of RRFD Mark III observations used for 1990-3.

The second category of catalogs includes those determined by other research groups. There are many possible candidates for comparison, of which only three are chosen. One important member of this category is the IERS catalog 90C01 [20], which combines individual CDP, IRIS, USNO, and JPL catalogs, with due attention paid to removal of rotational offsets and evaluation of formal uncertainties from disparate analyses. It contains the coordinates of 228 sources. Two GSFC catalogs were chosen to be representative of other external results. The first, here denoted GSFC89, is from [14]. It is based on 238,000 CDP and IRIS observations through early 1988 and contains 182 sources. A somewhat premature attempt was made to tie these source coordinates to the optical FK5 frame, which accounts for the large ($\approx$25 nrad) rotation in right ascension that is required to make this catalog coincide with any conventional radio catalog. A later Goddard catalog, denoted GSFC90 [15], extends the CDP and IRIS database and adds NAVNET [34] and southern hemisphere astrometric experiments, for a total of 461,000 observations of 318 sources.

Pairwise comparisons were made between the present source catalog and the above five collections of source positions derived from VLBI data. Prior to comparing the source coordinates, three-dimensional rotational offsets were calculated and removed for each pair in order to account for the different right ascension and nutation reference points used in deriving each catalog. These rotational offsets are a manifestation of the different methods used to define the orientation of the celestial reference frame for each catalog. Tables 7 and 8 give the magnitudes of these rotational offsets (whose uncertainties are of the order of 0.1 nrad), as well as the χ^2 per degree of freedom (χ^2_ν) in the least-squares solution determining the rotational transformations. After the rotation is applied (to the catalog other than 1990-3), the right ascension differences are scaled to arc-length differences by applying the factor cos (declination), and then RMS differences are calculated for both source coordinates. Note that all the catalogs involved in the comparisons (with the exception of 1987-1) were generated by fits that corrected the 1980 IAU nutation and precession errors by estimating either daily CEP orientation or nutation amplitudes and the precession constant.

Statistical analysis of uncertainties is problematic in cases like the present, where the same parameters are estimated from partially overlapping data. When this work is extended to include databases through 1991, a more complete statistical assessment will need to be performed. For the present, the covariance matrices for both catalogs are assumed to be diagonal, and the uncertainty of the difference of a given coordinate is assumed to be the root sum square of the individual 1σ uncertainties. In previous work, neglecting off-diagonal covariances somewhat underestimated the true errors.

From Table 7, it can be seen that agreement of JPL 1990-3 with the other two JPL catalogs is reasonable, at the level of the formal uncertainties. Rotational offsets are as large as 7 nrad for 1987-1, but much smaller for the more recent 1991-1. This is a manifestation of precession/nutation model deficiencies that were not as well corrected for 1987-1 as in more recent fits. Root-mean-square RA and declination differences are nearly consistent with the uncertainty level of the catalogs ($\approx$10 nrad for 1987-1 and $<$ 5 nrad for 1991-1 and 1990-3). The χ^2_ν(RA) values of 2.0 and 1.8 indicate some problem with right ascensions that is not encountered with declinations. In order to test whether the comparisons are being distorted by selection of sources, the two comparisons were repeated, including only sources that have formal σ's smaller than 5 nrad in both catalogs. Results for rotational offsets and χ^2_ν's are essentially unchanged, and the RMS differences decrease to approximately 4 and 3 nrad for 1987-1 and 1991-1, respectively.

Comparisons with the IERS catalog and two GSFC catalogs in Table 8 paint a more pessimistic picture than the intra-JPL comparisons. Rotational offsets are as large as 10 nrad (the 24-nrad rotation of GSFC89 was already mentioned above), RMS differences are slightly higher than 5 nrad, and χ^2_ν's range from 2 to 4. A 5-nrad cut on input catalog errors decreases the RMS differences slightly but raises the χ^2_ν's even further. This suggests that the formal uncertainties are underestimating true errors due to some systematic effects coming into play at the nanoradian level. When the catalog formal σ's are root sum squared with 2 nrad for all coordinates of each catalog pair in the comparisons, the χ^2_ν's are reduced to the 0.8–1.4 range; a slightly larger additive error (3 nrad) is required in the IERS90 comparison. Until further work identifies the source of the 2–3-nrad systematic errors, these results place a lower limit on the accuracy achievable in source position determinations. To be investigated are tropospheric covariance, the consequences of UTPM errors, a detailed comparison of modeling and analysis procedures, and proper motion or time-varying source structure. Approximately 100 sources show formal position uncertainties of 2 nrad or smaller in the JPL 1990-3 catalog. Indications are that the low σ's are solely due to the extremely large number of observations, and do not properly reflect presently unidentified and unmodeled systematic errors.

In conclusion, the addition of several hundred thousand non-DSN VLBI observations to the DSN data set in a fit determining a radio reference frame has the beneficial effects of checking consistency of source coordinates derived from disparate sets of baselines and revealing modeling deficiencies at the 2-nrad level. Considerable improvement is seen in the formal uncertainties (Fig. 1 versus Fig. 2), nearly 50 percent of the 1990-3 uncertainties are brought below the level of presently unidentified systematic effects. A similar level of resolution may not have been reached solely with DSN data for another year or two. It appears that the true accuracy of the JPL 1990-3 catalog is approximately at the 5-nrad level.

VI. Conclusions

Source angular coordinates of 216 extragalactic objects are derived from a database that includes the majority of the world's astrometric VLBI measurements through 1990. Care has been taken to eliminate some known sources of systematic error, in particular the inadequacy of the present standard precession/nutation model. The formal uncertainties of these JPL 1990-3 source positions are predominantly smaller than 5 nrad. Consistency tests indicate that the formal errors are overoptimistic, especially those below 2 to 3 nrad. The 2- to 3-nrad limit appears to be the point at which unknown systematics dominate. In spite of these systematics, comparisons with source coordinates from independent analyses of data that partly overlap the database used here show that the 1990-3 positions agree at approximately the 5-nrad level. This catalog may thus be one of the first to exhibit true 5-nrad accuracy. Consistency with the non-DSN data in the analysis, with its greater variety of baseline orientations and lengths, indicates that no serious systematic errors are present in the DSN-only data that might be introduced by the DSN baseline geometry, particularly the extremely long California–Australia baseline. Consistency with GSFC catalogs also provides an indirect verification that there are no outstanding discrepancies between JPL and GSFC modeling and estimation software at the 5-nrad level.

The status of the 1990-3 reference frame relative to future mission requirements remains to be fully characterized. When used with the CEP model of Table 6, the 1990-3 source coordinates are expected to yield accurate source coordinates of date several years into the future. If the true accuracy of this catalog is at the 5-nrad level, as indicated by the above-mentioned comparisons, then it is very close to satisfying Galileo specifications. The TOPEX/POSEIDON S-/X-band and preliminary Cassini Ka-band (32-GHz) 3-nrad requirements are more difficult to meet; however, many of the errors in constructing a Ka-band reference frame should be the same as those for the present S-/X-band frame. It is expected that further analytical refinements and acquisition of additional VLBI measurements will permit achieving the 3-nrad level within the next few years.

Future data analysis is planned along lines similar to that presented here, incorporating the more recent high-quality DSN Mark III data, as well as updates of the TEMPO, CDP, and IRIS databases. Empirical corrections for two of the known causes of systematic error (source structure and troposphere mismodeling) will be incorporated in future parameter estimates. Including LLR data extending back to 1969 would also be of substantial help in reducing the precession-nutation correlations [33]. Such fits are expected to reduce source coordinate uncertainties further, to better characterize the true accuracies, and to satisfy future navigation requirements for a radio reference frame.

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Table 1. Summary of VLBI observing programs

Program	N_{stn}	N_{bsl}	Time period	N_{ses}	N_{src}	N_{obs}
CDP	31	144	79/ 8 – 89/12	178	76	134,627
IRIS	8	24	84/ 1 – 90/ 6	452	31	168,119
TEMPO	3*	3*	80/ 7 – 90/ 9	665	106	7,324
RRFD MkII	3*	2*	78/10 –89/ 4	65	230	8,520
RRFD MkIII	3*	2*	88/ 8 – 90/ 7	13	214	1,144
Total	34	147	78/10 – 90/ 9	1373	230	319,734

*DSN Deep Space Communications Complex

Table 2. Noise characteristics of VLBI data

Program	N_{obs}	RMS data noise, psec	RMS added noise, psec
CDP	134,627	100	77
IRIS	168,119	94	66
TEMPO	7,324	464	260
RRFD MkII	8,520	395	158
RRFD MkIII	1,144	65	50

Table 3. Elevation-angle distributions of VLBI data

Program	f_{10}	f_{20}	f_{30}
CDP	0.020	0.129	0.278
IRIS	0.023	0.111	0.218
TEMPO	0.066	0.310	0.548
RRFD	0.065	0.293	0.510

Table 4. RMS delay and rate residuals of VLBI data

Program	Delay, psec	Delay rate, fsec/sec
CDP	96	113
IRIS	86	81
TEMPO	448	109
RRFD MkII	336	134
RRFD MkIII	87	117
All	123	100

Table 5. Source coordinates from combined VLBI measurements, 1978–90

IAU name	Common name	Mean observation epoch	Number of observations	Right ascension			Error, msec	Declination			Error, mas	RA, dec. correlation
				hr	min	sec		d	m	asec		
0008−264	P 0008−264	1984.667	38	0	11	1.246868	0.071	−26	12	33.37761	0.81	−0.933
0013−005	P 0013−00	1989.589	8	0	16	11.088443	0.151	−0	15	12.44239	2.25	−0.989
0016+731	0016+731	1988.839	33	0	19	45.785908	0.131	73	27	30.01964	0.39	0.102
0019+058	P 0019+058	1984.773	50	0	22	32.441219	0.026	6	8	4.26917	0.77	−0.570
0048−097	P 0048−09	1989.463	344	0	50	41.317356	0.007	−9	29	5.20976	0.12	−0.195
0104−408	P 0104−408	1985.701	98	1	6	45.108147	0.060	−40	34	19.95992	0.45	−0.875
0106+013	P 0106+01	1986.699	12430	1	8	38.771065	0.002	1	35	0.31787	0.06	−0.088
0111+021	P 0111+021	1983.353	37	1	13	43.145073	0.098	2	22	17.31556	1.58	−0.913
0112−017	P 0112−017	1988.929	24	1	15	17.099895	0.015	−1	27	4.57657	0.29	−0.779
0113−118	P 0113−118	1984.385	61	1	16	12.521992	0.035	−11	36	15.43412	0.52	−0.902
0119+115	P 0119+11	1988.888	22	1	21	41.595005	0.015	11	49	50.41420	0.32	−0.761
0119+041	GC 0119+04	1990.096	1023	1	21	56.861675	0.004	4	22	24.73470	0.15	−0.252
0133+476	DA 55	1984.855	172	1	36	58.594818	0.010	47	51	29.10011	0.25	−0.365
0146+056	0146+056	1988.710	14	1	49	22.370842	0.033	5	55	53.57026	0.61	−0.859
0149+218	P 0149+21	1989.085	8	1	52	18.059040	0.048	22	7	7.70014	0.77	−0.815
0201+113	P 0201+113	1987.110	15	2	3	46.657017	0.025	11	34	45.41072	0.56	−0.748
0202+149	P 0202+14	1985.729	123	2	4	50.413879	0.008	15	14	11.04385	0.15	−0.701
0208−512	P 0208−512	1988.393	3	2	10	46.199532	0.271	−51	1	1.88993	1.83	−0.886
0212+735	0212+735	1987.203	20017	2	17	30.813374	0.009	73	49	32.62226	0.03	−0.437
0221+067	GC 0221+06	1988.948	12	2	24	28.428144	0.027	6	59	23.34205	0.38	−0.900
0224+671	DW 0224+67	1981.836	868	2	28	50.051556	0.014	67	21	3.02982	0.10	−0.386
0229+131	P 0229+13	1987.214	11202	2	31	45.894047	0.002	13	22	54.71671	0.04	−0.164
0234+285	CTD 20	1987.195	6544	2	37	52.405674	0.003	(28	48	8.99038)	(0.00)	(0.000)
0235+164	GC 0235+16	1982.164	903	2	38	38.930103	0.006	16	36	59.27496	0.11	−0.666
0239+108	OD 166	1985.359	76	2	42	29.170900	0.030	11	1	0.72751	0.37	−0.931
0250+178	GC 0250+17	1989.677	12	2	53	34.882183	0.037	18	5	42.52564	1.05	−0.566
0256+075	OD 094.7	1983.652	32	2	59	27.076651	0.036	7	47	39.64091	1.83	−0.399
0300+470	OE 400	1988.855	3466	3	3	35.242237	0.004	47	16	16.27578	0.04	−0.306
0306+102	0306+102	1989.282	14	3	9	3.623471	0.028	10	29	16.34191	0.42	−0.895
0309+411	0309+411	1987.721	12	3	13	1.962166	0.035	41	20	1.18315	1.01	−0.157
0316+413	3C 84	1984.601	308	3	19	48.160145	0.010	41	30	42.10449	0.18	−0.044
0317+188	P 0317+188	1989.671	11	3	19	51.256706	0.012	19	1	31.29180	0.32	−0.646
0326+277	0326+277	1988.134	10	3	29	57.669388	0.041	27	56	15.49998	0.53	−0.671
0332−403	P 0332−403	1983.633	49	3	34	13.654550	0.111	−40	8	25.39683	0.81	−0.882
0333+321	NRAO 140	1983.205	123	3	36	30.107639	0.029	32	18	29.34300	0.30	−0.838
0336−019	CTA 26	1985.726	89	3	39	30.937748	0.011	−1	46	35.80241	0.26	−0.361

Table 5 (contd)

IAU name	Common name	Mean observation epoch	Number of observations	Right ascension hr	Right ascension min	Right ascension sec	Error, msec	Declination d	Declination m	Declination asec	Error, mas	RA, dec. correlation
0342+147	0342+147	1987.811	28	3	45	6.416506	0.034	14	53	49.55854	0.46	−0.821
0355+508	NRAO 150	1982.000	1847	3	59	29.747309	0.007	50	57	50.16193	0.07	−0.238
0400+258	CTD 26	1987.340	3	4	3	5.586178	0.180	26	0	1.50284	1.83	−0.973
0402−362	P 0402−362	1985.129	104	4	3	53.749821	0.038	−36	5	1.91249	0.41	−0.915
0406−127	0406−127	1989.466	4	4	9	5.769566	0.151	−12	38	48.14061	2.13	−0.983
0406+121	GC 0406+12	1984.235	96	4	9	22.008692	0.027	12	17	39.84791	0.42	−0.766
0409+229	P 0409+22	1989.663	13	4	12	43.666847	0.016	23	5	5.45394	0.36	−0.545
0420−014	P 0420−01	1988.604	6728	4	23	15.800686	0.002	−1	20	33.06435	0.05	−0.254
0420+417	VRO 41.04.01	1980.724	11	4	23	56.009869	0.202	41	50	2.71570	2.89	−0.458
0423+233	GC 0423+23	1989.671	11	4	26	55.734795	0.011	23	27	39.63453	0.31	−0.565
0425+048	P 0425+048	1987.655	26	4	27	47.570328	0.104	4	57	8.32905	1.47	−0.977
0426+273	0426+273	1989.666	14	4	29	52.960754	0.013	27	24	37.87780	0.42	−0.472
0430+052	3C 120	1981.230	141	4	33	11.095490	0.023	5	21	15.62231	0.77	−0.558
0434−188	P 0434−188	1985.211	100	4	37	1.482675	0.017	−18	44	48.61311	0.29	−0.715
0438−436	P 0438−43	1982.778	40	4	40	17.179842	0.116	−43	33	8.60147	0.78	−0.864
0440+345	0440+345	1989.178	13	4	43	31.635271	0.035	34	41	6.66321	0.41	−0.772
0446+112	P 0446+11	1989.025	20	4	49	7.671068	0.027	11	21	28.59826	0.48	−0.745
0451−282	P 0451−28	1983.885	18	4	53	14.646607	0.096	−28	7	37.32491	1.17	−0.962
0454−234	0454−234	1990.200	613	4	57	3.179160	0.006	−23	24	52.01993	0.26	−0.326
0458+138	P 0458+138	1989.351	10	5	1	45.270744	0.106	13	56	7.22257	1.38	−0.968
0459+060	GC 0459+06	1989.592	8	5	2	15.445878	0.139	6	9	7.49573	2.01	−0.984
0500+019	0500+019	1988.822	12	5	3	21.197086	0.034	2	3	4.67747	0.51	−0.911
0502+049	P 0502+049	1989.433	11	5	5	23.184755	0.094	4	59	42.72493	1.29	−0.987
0454+844	0454+844	1986.115	67	5	8	42.363876	0.121	84	32	4.54414	0.21	0.019
0506+101	P 0506+101	1988.770	20	5	9	27.457073	0.027	10	11	44.60062	0.42	−0.888
0507+179	P 0507+17	1987.671	25	5	10	2.369150	0.028	18	0	41.58187	0.43	−0.704
0511−220	P 0511−220	1989.307	6	5	13	49.114277	0.032	−21	59	16.09140	0.59	−0.794
0528+134	P 0528+134	1987.290	12691	5	30	56.416737	0.001	13	31	55.15025	0.04	−0.400
0537−441	P 0537−441	1985.159	134	5	38	50.361164	0.074	−44	5	8.93651	0.59	−0.912
0537−158	P 0537−158	1988.071	3	5	39	32.010201	0.067	−15	50	30.32208	3.36	−0.395
0536+145	0536+145	1988.410	28	5	39	42.366028	0.025	14	33	45.56190	0.36	−0.911
0544+273	0544+273	1987.942	17	5	47	34.148983	0.046	27	21	56.84298	0.73	−0.700
0552+398	DA 193	1986.888	25513	5	55	30.805620	0.002	39	48	49.16539	0.03	−0.395
0556+238	0556+238	1988.579	31	5	59	32.033134	0.014	23	53	53.92704	0.27	−0.553
0600+177	0600+177	1988.235	28	6	3	9.130286	0.029	17	42	16.81109	0.40	−0.913
0605−085	P 0605−08	1981.668	12	6	7	59.699158	0.105	−8	34	49.97785	2.02	−0.766

Table 5 (contd)

IAU name	Common name	Mean observation epoch	Number of observations	Right ascension			Error, msec	Declination			Error, mas	RA, dec. correlation
				hr	min	sec		d	m	asec		
0611+131	0611+131	1989.633	5	6	13	57.692436	0.210	13	6	45.40760	2.82	−0.989
0642+214	3C 166	1988.667	15	6	45	24.099539	0.031	21	21	51.20209	0.48	−0.783
0657+172	0657+172	1987.192	23	7	0	1.525573	0.043	17	9	21.70139	0.80	−0.805
0722+145	P 0722+145	1989.203	19	7	25	16.807827	0.027	14	25	13.74644	0.39	−0.916
0723−008	DW 0723−00	1983.649	82	7	25	50.639908	0.041	−0	54	56.54408	0.71	−0.889
0727−115	P 0727−11	1988.978	2111	7	30	19.112436	0.003	−11	41	12.60000	0.07	−0.306
0735+178	P 0735+17	1985.148	82	7	38	7.393737	0.009	17	42	18.99918	0.21	−0.686
0736+017	P 0736+01	1989.726	16	7	39	18.033884	0.015	1	37	4.61811	0.26	−0.892
0738+313	OI 363	1984.907	17	7	41	10.703663	0.062	31	12	0.22568	0.54	−0.977
0742+103	DW 0742+10	1987.855	1044	7	45	33.059521	0.004	10	11	12.69277	0.12	−0.463
0743+259	GC 0743+25	1988.918	15	7	46	25.874182	0.032	25	49	2.13490	0.52	−0.708
0745+241	B2 0745+24	1985.049	50	7	48	36.109272	0.031	24	0	24.11141	0.65	−0.553
0748+126	P 0748+126	1983.493	68	7	50	52.045738	0.030	12	31	4.82853	0.57	−0.740
0754+100	P 0754+100	1989.022	14	7	57	6.642954	0.028	9	56	34.85172	0.50	−0.803
0805−077	P 0805−07	1987.825	8	8	8	15.535896	0.148	−7	51	9.88473	2.29	−0.998
0814+425	OJ 425	1987.175	257	8	18	15.999655	0.014	42	22	45.41528	0.18	−0.365
0823+033	P 0823+033	1986.860	294	8	25	50.338337	0.006	3	9	24.52047	0.13	−0.636
0827+243	B2 0827+24	1983.847	17	8	30	52.086189	0.035	24	10	59.82098	0.46	−0.943
0836+710	4C 71.07	1981.082	17	8	41	24.365801	0.252	70	53	42.17249	1.67	0.161
0851+202	OJ 287	1986.910	20630	(8	54	48.874920)	(0.000)	(20	6	30.64131)	(0.00)	(0.000)
0859−140	P 0859−14	1984.361	19	9	2	16.831095	0.129	−14	15	30.87777	1.60	−0.971
0859+470	OJ 499	1984.806	34	9	3	3.990097	0.068	46	51	4.13771	1.85	−0.237
0912+029	P 0912+029	1989.279	14	9	14	37.913448	0.044	2	45	59.24608	0.68	−0.975
0919−260	0919−260	1989.603	16	9	21	29.354017	0.149	−26	18	43.38887	3.74	−0.920
0920−397	P 0920−39	1987.932	6	9	22	46.417778	0.206	−39	59	35.06447	2.14	−0.976
0923+392	4C 39.25	1986.915	23656	9	27	3.013901	0.002	39	2	20.85215	0.03	0.010
0925−203	P 0925−203	1987.866	11	9	27	51.823792	0.160	−20	34	51.22625	2.19	−0.993
0953+254	OK 290	1980.571	86	9	56	49.875427	0.018	25	15	16.04907	0.60	−0.725
1012+232	1012+232	1989.027	20	10	14	47.065491	0.029	23	1	16.57087	0.39	−0.959
1022+194	GC 1022+19	1989.603	8	10	24	44.809582	0.026	19	12	20.41663	0.53	−0.774
1034−293	P 1034−293	1989.093	535	10	37	16.079710	0.009	−29	34	2.81403	0.14	−0.499
1038+064	OL 064.5	1984.281	64	10	41	17.162470	0.027	6	10	16.92338	0.72	−0.603
1042+071	P 1042+071	1989.195	12	10	44	55.911251	0.036	6	55	38.26318	0.66	−0.875
1044+719	1044+719	1988.317	11	10	48	27.619911	0.117	71	43	35.93801	0.66	−0.479
1055+018	P 1055+01	1988.883	2635	10	58	29.605196	0.002	1	33	58.82394	0.08	−0.424
1104−445	P 1104−445	1987.230	132	11	7	8.694243	0.083	−44	49	7.62063	0.49	−0.877

Table 5 (contd)

IAU name	Common name	Mean observation epoch	Number of observations	Right ascension			Error, msec	Declination			Error, mas	RA, dec. correlation
				hr	min	sec		d	m	asec		
1111+149	GC 1111+14	1984.858	23	11	13	58.695099	0.041	14	42	26.95282	0.62	−0.974
1116+128	P 1116+12	1984.281	7	11	18	57.301376	0.043	12	34	41.71983	0.71	−0.955
1123+264	P 1123+26	1985.652	131	11	25	53.711910	0.010	26	10	19.97890	0.17	−0.741
1127−145	P 1127−14	1982.901	56	11	30	7.052641	0.064	−14	49	27.38946	0.99	−0.876
1128+385	GC 1128+38	1984.798	82	11	30	53.282635	0.023	38	15	18.54746	0.50	−0.242
1144+402	1144+402	1986.348	1082	11	46	58.297935	0.006	39	58	34.30446	0.07	−0.066
1144−379	P 1144−379	1986.151	211	11	47	1.370696	0.041	−38	12	11.02475	0.36	−0.902
1145−071	1145−071	1989.367	7	11	47	51.553970	0.025	−7	24	41.14088	0.71	−0.580
1148−001	P 1148−00	1983.107	23	11	50	43.870846	0.075	−0	23	54.20517	1.25	−0.891
1150+812	1150+812	1989.044	43	11	53	12.499044	0.142	80	58	29.15409	0.33	0.247
1156+295	GC 1156+29	1989.093	1331	11	59	31.833910	0.004	29	14	43.82693	0.06	−0.144
1219+285	ON 231	1980.571	113	12	21	31.690565	0.016	28	13	58.50143	0.61	−0.639
1222+037	P 1222+037	1983.849	60	12	24	52.421879	0.031	3	30	50.29426	0.60	−0.804
1226+023	3C 273	1985.978	11902	12	29	6.699723	0.002	2	3	8.59916	0.06	0.129
1243−072	1243−072	1989.997	9	12	46	4.232075	0.023	−7	30	46.57384	0.39	−0.834
1244−255	P 1244−255	1985.767	118	12	46	46.802166	0.037	−25	47	49.29095	0.44	−0.922
1253−055	3C 279	1987.211	710	12	56	11.166497	0.005	−5	47	21.52418	0.16	0.153
1302−102	P 1302−102	1989.652	15	13	5	33.014919	0.019	−10	33	19.42628	0.36	−0.738
1308+326	B2 1308+32	1987.403	2312	13	10	28.663879	0.004	32	20	43.78286	0.06	−0.205
1313−333	OP−322	1984.363	45	13	16	7.985952	0.093	−33	38	59.17341	1.00	−0.947
1315+346	OP 326	1990.151	4	13	17	36.494152	0.035	34	25	15.93075	1.46	0.839
1335−127	DW 1335−12	1989.285	1379	13	37	39.782745	0.004	−12	57	24.69304	0.10	−0.148
1342+662	GC 1342+662	1983.849	35	13	43	45.959625	0.062	66	2	25.74482	0.44	−0.053
1342+663	GC 1342+663	1984.708	162	13	44	8.679707	0.034	66	6	11.64348	0.22	0.150
1349−439	P 1349−439	1985.833	45	13	52	56.535149	0.143	−44	12	40.39031	0.90	−0.890
1354+195	P 1354+19	1986.707	739	13	57	4.436650	0.006	19	19	7.37252	0.11	−0.396
1354−152	OP−192	1989.104	18	13	57	11.245065	0.029	−15	27	28.78804	0.38	−0.913
1404+286	OQ 208	1986.855	16207	14	7	0.394422	0.002	28	27	14.68967	0.05	−0.291
1406−076	P 1406−076	1989.701	7	14	8	56.481178	0.034	−7	52	26.66544	0.54	−0.765
1418+546	GC 1418+54	1985.652	531	14	19	46.597424	0.014	54	23	14.78695	0.15	−0.163
1424−418	P 1424−41	1988.396	5	14	27	56.297581	0.132	−42	6	19.44042	0.87	−0.833
1430−178	OQ−151	1983.981	23	14	32	57.690651	0.273	−18	1	35.25099	3.75	−0.974
1443−162	1443−162	1989.805	6	14	45	53.376358	0.093	−16	29	1.61882	1.25	−0.956
1445−161	P 1445−16	1989.518	12	14	48	15.054192	0.035	−16	20	24.54957	0.50	−0.908
1502+106	OR 103	1988.423	2420	15	4	24.979795	0.003	10	29	39.19889	0.10	−0.081
1504−166	P 1504−167	1984.760	64	15	7	4.786958	0.022	−16	52	30.26719	0.63	−0.523

Table 5 (contd)

IAU name	Common name	Mean observation epoch	Number of observations	Right ascension			Error, msec	Declination			Error, mas	RA, dec. correlation
				hr	min	sec		d	m	asec		
1510−089	P 1510−08	1986.814	244	15	12	50.532932	0.013	−9	5	59.82971	0.26	−0.707
1511−100	P 1511−100	1989.405	9	15	13	44.893406	0.027	−10	12	0.26344	0.58	−0.671
1514−241	P 1514−24	1989.545	10	15	17	41.813305	0.058	−24	22	19.47806	0.70	−0.952
1519−273	P 1519−273	1986.975	180	15	22	37.676056	0.049	−27	30	10.78650	0.57	−0.938
1532+016	P 1532+01	1988.806	16	15	34	52.453609	0.034	1	31	4.20772	0.53	−0.908
1548+056	DW 1548+05	1986.819	2423	15	50	35.269226	0.003	5	27	10.44892	0.09	0.113
1555+001	DW 1555+00	1985.066	96	15	57	51.433945	0.025	−0	1	50.41273	0.61	−0.651
1611+343	DA 406	1989.841	1744	16	13	41.064259	0.003	34	12	47.90900	0.08	−0.171
1614+051	P 1614+051	1988.544	13	16	16	37.556808	0.028	4	59	32.73700	0.45	−0.875
1622−253	P 1622−253	1990.195	525	16	25	46.891602	0.007	−25	27	38.32558	0.28	−0.341
1633+382	GC 1633+38	1988.861	5684	16	35	15.492970	0.003	38	8	4.50046	0.06	−0.070
1637+574	P 1637+574	1983.521	271	16	38	13.456281	0.021	57	20	23.97837	0.24	0.038
1638+398	NRAO 512	1983.405	119	16	40	29.632765	0.021	39	46	46.02849	0.30	−0.599
1642+690	1642+690	1980.699	1079	16	42	7.848453	0.015	68	56	39.75576	0.10	−0.060
1641+399	3C 345	1985.825	19307	16	42	58.809959	0.002	39	48	36.99369	0.06	−0.008
1655+077	OS 092	1987.989	27	16	58	9.011436	0.025	7	41	27.54106	0.71	−0.579
1656+053	DW 1656+05	1982.948	20	16	58	33.447254	0.117	5	15	16.44569	1.76	−0.992
1657−261	P 1657−261	1985.153	39	17	0	53.154152	0.046	−26	10	51.72603	0.63	−0.855
1706−174	OT−111	1984.986	41	17	9	34.345371	0.048	−17	28	53.36405	0.77	−0.881
1717+178	GC 1717	1981.466	25	17	19	13.048463	0.030	17	45	6.43817	1.60	0.058
1730−130	NRAO 530	1987.879	1156	17	33	2.705772	0.005	−13	4	49.54746	0.14	−0.183
1738+476	OT 465	1985.490	93	17	39	57.129055	0.023	47	37	58.36189	0.57	−0.243
1739+522	4C 51.37	1989.997	2728	17	40	36.977840	0.004	52	11	43.40747	0.06	0.066
1741−038	P 1741−038	1988.664	5917	17	43	58.856140	0.002	−3	50	4.61590	0.10	0.135
1748+701	1749+701	1982.658	138	17	48	32.840473	0.064	70	5	50.76680	0.27	−0.053
1749+096	OT 081	1987.660	1447	17	51	32.818584	0.003	9	39	0.72882	0.10	0.061
1803+784	1803+784	1987.488	23352	18	0	45.683819	0.009	78	28	4.01828	0.04	0.075
1807+698	3C 371	1984.948	238	18	6	50.680634	0.038	69	49	28.10885	0.20	−0.021
1821+107	P 1821+10	1985.019	45	18	24	2.855270	0.034	10	44	23.77293	1.38	−0.523
1845+797	3C 390.3	1979.901	16	18	42	8.989495	0.362	79	46	17.12646	0.58	−0.118
1908−201	OV−213	1986.907	32	19	11	9.652929	0.035	−20	6	55.10953	0.47	−0.901
1920−211	OV−235	1988.276	37	19	23	32.189861	0.030	−21	4	33.33339	0.43	−0.897
1921−293	OV−236	1988.921	1040	19	24	51.055946	0.006	−29	14	30.12061	0.15	−0.252
1923+210	OV 239.7	1987.244	88	19	25	59.605373	0.016	21	6	26.16149	0.26	−0.799
1928+738	1928+738	1981.460	51	19	27	48.494961	0.089	73	58	1.57013	0.71	−0.293
1936−155	P 1936−15	1988.959	16	19	39	26.657772	0.031	−15	25	43.05868	0.48	−0.886

Table 5 (contd)

IAU name	Common name	Mean observation epoch	Number of observations	Right ascension			Error, msec	Declination			Error, mas	RA, dec. correlation
				hr	min	sec		d	m	asec		
1954+513	1954+513	1989.238	24	19	55	42.738186	0.043	51	31	48.54832	0.48	0.026
1958−179	OV−198	1986.285	119	20	0	57.090458	0.023	−17	48	57.67260	0.33	−0.855
2008−159	P 2008−159	1988.844	20	20	11	15.710927	0.027	−15	46	40.25305	0.42	−0.868
2021+614	OW 637	1987.616	101	20	22	6.681649	0.032	61	36	58.80481	0.50	−0.009
2030+547	OW 551	1981.630	14	20	31	47.958549	0.197	54	55	3.14788	3.01	−0.080
2029+121	P 2029+121	1984.093	33	20	31	54.994236	0.062	12	19	41.33965	1.26	−0.715
2037+511	3C 418	1988.150	359	20	38	37.034779	0.010	51	19	12.66291	0.11	0.217
2113+293	B2 2113+29B	1986.307	178	21	15	29.413473	0.010	29	33	38.36657	0.23	−0.162
2121+053	OX 036	1989.107	5908	21	23	44.517380	0.002	5	35	22.09376	0.08	0.113
2128−123	P 2128−12	1988.831	21	21	31	35.261684	0.025	−12	7	4.79540	0.41	−0.849
2131−021	P 2131−021	1988.885	25	21	34	10.309592	0.016	−1	53	17.23844	0.32	−0.759
2134+004	P 2134+004	1985.852	6648	21	36	38.586308	0.002	0	41	54.21443	0.10	−0.111
2145+067	P 2145+06	1986.433	2454	21	48	5.458668	0.003	6	57	38.60450	0.08	0.102
2149+056	OX 082	1984.142	78	21	51	37.875381	0.039	5	52	12.95605	0.63	−0.873
2155−152	OX−192	1985.260	51	21	58	6.281964	0.089	−15	1	9.32834	1.26	−0.961
2200+420	VRO 42.22.01	1986.403	15662	22	2	43.291370	0.003	42	16	39.98008	0.04	0.405
2201+315	B2 2201+31A	1983.433	24	22	3	14.975830	0.038	31	45	38.27049	0.70	0.170
2216−038	P 2216−03	1987.052	2789	22	18	52.037716	0.003	−3	35	36.87867	0.10	0.068
2223−052	3C 446	1985.274	68	22	25	47.259274	0.018	−4	57	1.39028	0.40	−0.687
2227−088	P 2227−08	1988.855	19	22	29	40.084297	0.026	−8	32	54.43421	0.43	−0.891
2229+695	2229+695	1988.423	16	22	30	36.469852	0.092	69	46	28.07718	0.39	0.065
2230+114	CTA 102	1985.129	125	22	32	36.408909	0.013	11	43	50.90439	0.24	−0.734
2234+282	GC 2234+28	1988.735	3182	22	36	22.470861	0.003	28	28	57.41359	0.06	0.197
2243−123	OY−172.6	1985.112	121	22	46	18.231953	0.019	−12	6	51.27657	0.32	−0.826
2245−328	P 2245−328	1984.167	65	22	48	38.685780	0.045	−32	35	52.18752	0.49	−0.914
2251+158	3C 454.3	1986.145	13876	22	53	57.747932	0.002	16	8	53.56100	0.05	0.315
2253+417	GC 2253+41	1983.351	54	22	55	36.707783	0.043	42	2	52.53282	0.97	0.032
2254+074	GC 2254+07	1989.614	4	22	57	17.303083	0.159	7	43	12.30326	2.56	−0.962
2254+024	P 2254+024	1988.749	19	22	57	17.563122	0.047	2	43	17.51163	0.70	−0.945
2255−282	P 2255−282	1990.205	405	22	58	5.962849	0.008	−27	58	21.25589	0.33	−0.183
2318+049	GC 2318+04	1988.970	24	23	20	44.856579	0.025	5	13	49.95361	0.38	−0.904
2320−035	P 2320−035	1985.216	89	23	23	31.953726	0.024	−3	17	5.02289	0.40	−0.885
2335−027	P 2335−027	1989.570	8	23	37	57.339039	0.069	−2	30	57.62940	1.09	−0.917
2345−167	P 2345−16	1984.839	71	23	48	2.608478	0.038	−16	31	12.02106	0.56	−0.898
2351−154	2351−154	1989.367	9	23	54	30.195244	0.071	−15	13	11.21327	1.02	−0.948
2355−106	P 2355−106	1987.701	40	23	58	10.882395	0.033	−10	20	8.61091	0.55	−0.844

Table 6. JPL 1990-3 celestial ephemeris pole motion model

Index	Period, days	ΔA_ψ (in phase) (out of phase), nrad	ΔA_ϵ (in phase) (out of phase), nrad
1	6798.38	−22.1±1.7 7.7 0.7	8.2±0.3 10.3 0.2
2	3399.19	7.8±0.6 1.0 0.3	0.6±0.1 0.7 0.1
10	365.26	24.6±0.1 5.5 0.1	9.3±0.1 −0.9 0.1
9	182.62	6.9±0.1 −6.1 0.1	−2.4±0.1 −1.9 0.1
11	121.75	−1.0±0.1 0.1 0.1	0.8±0.1 0.1 0.1
32	27.55	−1.0±0.1 −0.6 0.1	−0.5±0.1 0.4 0.1
31	13.66	−2.7±0.2 0.6 0.2	1.4±0.1 −0.4 0.1
33	13.63	−2.0±0.2 0.1 0.2	0.6±0.1 0.3 0.1
—	433.20	−3.0±0.1 3.0 0.1	−0.6±0.1 −1.3 0.1
Precession, nrad/yr		−10.4±0.3	—
Offset		−61.3±1.6	9.4±0.3

Table 7. Comparisons of other JPL catalogs with JPL 1990-3

Catalog	1987-1	1991-1
Number of common sources	103	208
RMS uncertainty for common sources		
JPL 1990-3: RA $\cos\delta$ and dec., nrad	5.0, 4.4	6.3, 5.4
Other: RA $\cos\delta$ and dec., nrad	9.0, 8.6	4.8, 4.0
Rotational offsets, nrad x	−2.8	0.0
y	7.2	1.8
z	−3.1	0.5
χ^2 per degree of freedom	1.7	1.5
RMS difference, nrad: RA $\cos\delta$	7.5	5.2
dec.	10.8	5.8
χ^2 per degree of freedom: RA $\cos\delta$	2.0	1.8
dec.	1.3	1.1

Table 8. Comparisons of external catalogs with JPL 1990-3

Catalog	IERS90	GSFC89	GSFC90
Number of common sources	183	120	159
RMS uncertainty for common sources			
JPL 1990-3: RA $\cos\delta$ and dec., nrad	4.9, 4.3	4.7, 3.6	6.1 4.8
Other: RA $\cos\delta$ and dec., nrad	7.6, 6.8	5.7, 3.0	3.7 2.9
Rotational offsets, nrad x	1.4	10.2	−5.4
y	0.7	5.0	−11.9
z	0.3	−24.3	1.8
χ^2 per degree of freedom	3.6	2.7	3.8
RMS difference, nrad: RA $\cos\delta$	5.8	4.2	7.5
dec.	8.9	6.2	6.6
χ^2 per degree of freedom: RA $\cos\delta$	3.3	2.1	4.0
dec.	4.0	2.7	3.3

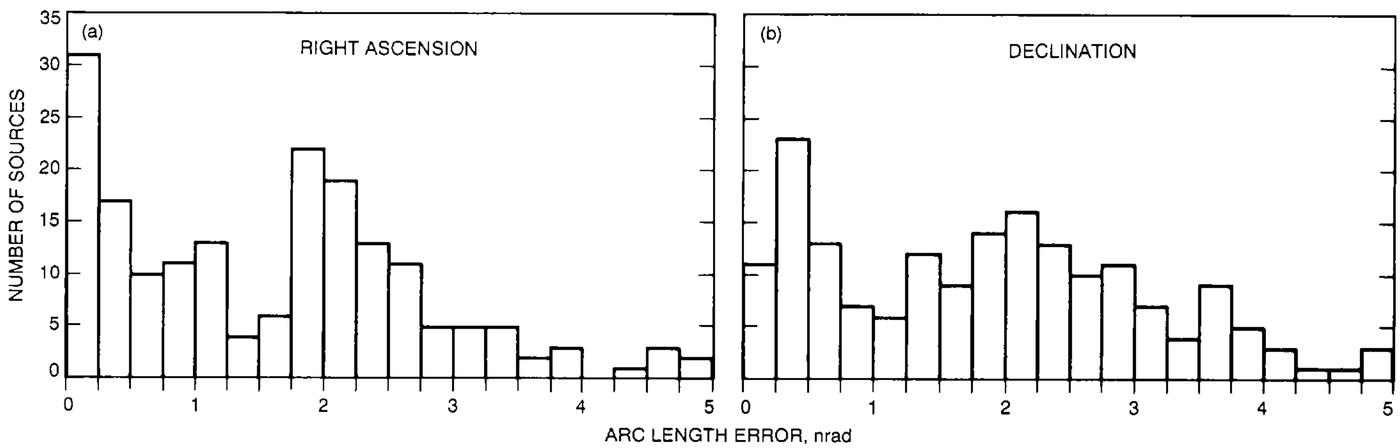

Fig. 1. Distribution of errors in (a) right ascension (arc length) and (b) declination for source coordinates in the catalog JPL 1990-3.

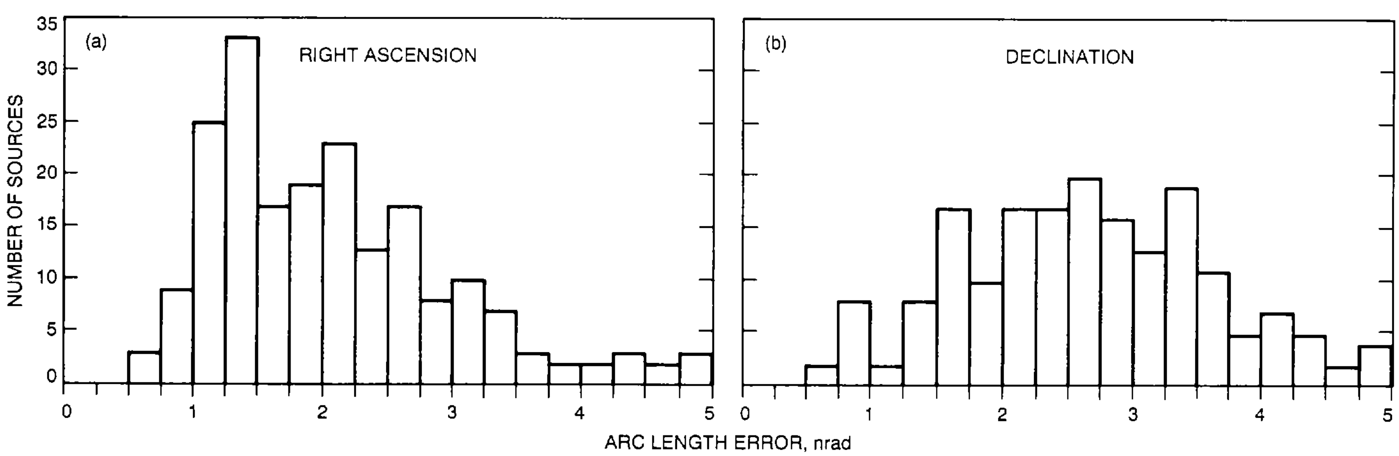

Fig. 2. Distribution of errors in (a) right ascension (arc length) and (b) declination for source coordinates in the TEMPO catalog JPL 1991-1.